Analysis of recovery efficiency in a high-temperature energy storage system

Mariene Gutierrez-Neri[1]*, Nick Buik*, Benno Drijver*, and Bas Godschalk*

[1]Dept of Hydrology and Geo-environmental Sciences, Faculty of Earth and Life Sciences, VU University Amsterdam. De Boelelaan 1085, 1081 HV Amsterdam, the Netherlands.

* IF Technology, Velperweg 37, PO Box 605, 6800 AP Arnhem, the Netherlands.

e-mail: m.gutierrez@iftechnology.nl

Introduction

The concept of Underground Thermal Energy Storage (UTES) has evolved from theory to the point where system feasibility has been demonstrated technically and commercially in particular for low-temperature applications. These types of systems are typically referred to as Aquifer Thermal Energy Storage (ATES). One of the most common applications of ATES is the heating and cooling of spaces.

In contrast, high-temperature energy storage (HTES) systems have received less attention. HTES applications (where the temperature ranges between 60-100°C) can be of significant value, especially in connection with energy sources which are not controlled by immediate demand such as residual heat (e.g. from power plants or industrial processes) or renewable sources such as geothermal or solar energy. By storing temporally the excess of energy, a better balance between the supply and demand can be obtained. It can also be applied as back-up capacity or to simply preserve the heat and energy. An overview of the different type of UTES systems and their most common applications is given in [1].

An important aspect of a HTES project is the recovery (or storage) efficiency, defined as the relation between the amount of recovered energy in one season and the amount stored during another season. This work presents the results of a modelling study on the hydro-thermal behaviour of an HTES system. Simulations are carried out to evaluate the influence of hydraulic, thermal, and operational parameters on the recovery efficiency.

Problem definition

The HTES system schematised in Figure 1 consists of a single storage/extraction well and functions as follows:

- The storage aquifer is assumed of infinite horizontal dimensions and is bounded by impermeable top and bottom layers
- The well is fully-penetrating
- No groundwater flow is assumed
- One storage cycle (3 months), a rest period (three months), an extraction cycle (3 months) followed by another rest period (3 months)
- The well injection and extraction rate are equal
- No 'cut-off' temperature is assumed (minimal utilisation temperature)

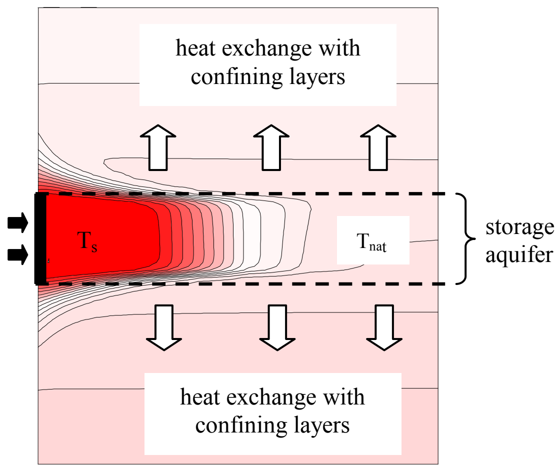

Figure 1 – *Development of the thermal front during storage mode.*

Modeling approach

The HTES system showed in Figure 1 is modelled using the computer programme HstWin-2D, a code specially developed for heat and solute transport in porous media. The code takes into account the dependency of the fluid properties such as viscosity and density on temperature and concentration changes [2]. A 2-D radial configuration is used to model the expected symmetrical effects around the storage/recovery well. The model domain has a thickness of 100 m and a radial extent of 500 m. A series of preliminary runs were carried out to test grid convergence. Appropriate results were obtained for square grid elements with $\Delta r=\Delta z=1$m within the thermal radius zone, then a series of grid cells with half that size, followed by a logarithmic increase in the grid elements. The cells rows immediately above and below the border of the aquifer and the confining layers were also halved. The maximum time step length is set to 0.5 days.

Sensitivity analysis

A series of sensitivity runs were carried out to study the effects of hydraulic, thermal and operational parameters on the recovery efficiency. The base case is listed in Table 1.

Parameter	Units	Value
Permeability	[D]	20
Anisotropy ratio	[-]	1
Porosity	[-]	0.35
Thickness	[m]	50
Storage Temp.	[°C]	90
Flow rate	[m^3/h]	50

Table 1- *Values used in the reference case.*

The base case assumes that the aquifer is at an initial (natural) temperature (T_{nat}) of 15°C, is homogenous and isotropic, and has a thickness (H) of 50 m. The well's flow rate (q) is 50 m^3/h and the storage temperature (T_s) is 90°C. The hydraulic parameters varied were the porosity (n), the intrinsic permeability (k_i), and the anisotropy ratio (k_h/k_v). The thermal parameters varied were the thermal conductivity of the medium (λ) initially assumed 2.5 W/mK. The operational variables changed were the storage temperature and well flow rate. A total of 12 HTES systems were simulated (see Table 2 for an overview).

Run	Variation	Values used
1	Base	
2	K_h/k_v	10
3	k_h	50 D
4	k_h	2 D
5	N	0.25
6	Ts	60°C
7	Q	100 m^3/h
8	λ	3 W/mK
9	H	20 m
10	H, k_h,	20 m; 5 D
11	H, k_h,Ts	20 m; 2 D; 60°C
12	H, k_h, Ts	20 m; 2 D; 90°C

Table 2 –*Overview of the simulation runs*

Results of the simulations

Temporal evolution

Figure 2 shows the hydro-thermal behaviour of the HTES system over a period of 5 years for the base case.

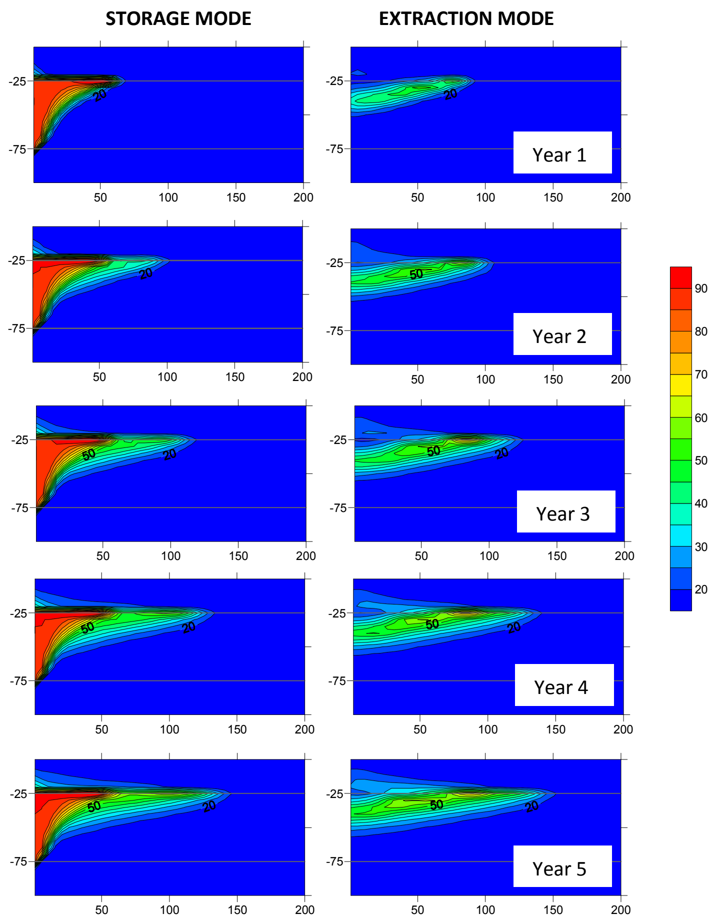

Figure 2 – *Temperature distributions during storage and extraction mode.*

Buoyancy effects carry the stored hot water towards the upper part of the aquifer and therefore colder temperatures are observed in the lower part of the aquifer. As a results, the temperature levels quickly drop during extraction mode. This can be observed in Figure 3.

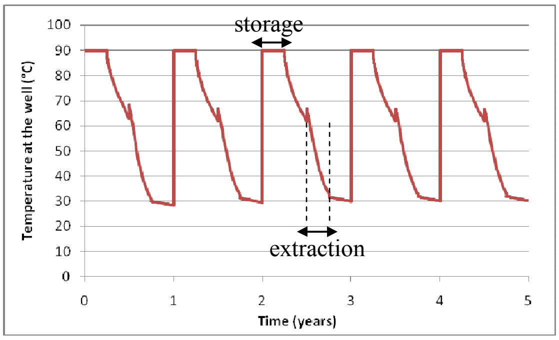

Figure 3 – *Temperature evolution in the well.*

After 4 years the thermal plume and extracted temperatures become relatively steady. The recovery efficiency obtained for the base case is about 40%

Effects of aquifer anisotropy, thickness and permeability

Figure 4 shows the isotherms that develop in an isotropic and anisotropic aquifer. The anisotropy ratio used is 10. The thermal plume is less buoyant in an anisotropic medium due to a lower vertical permeability. Higher temperatures and recovery efficiencies are favoured.

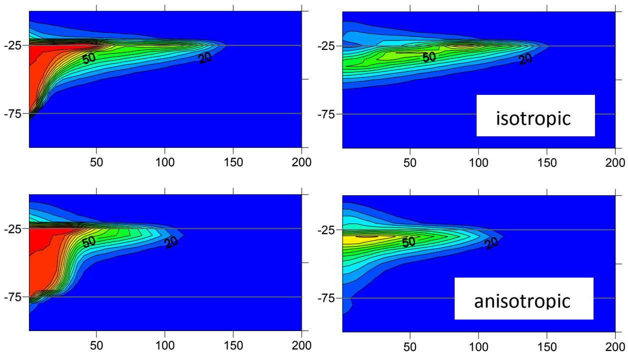

Figure 4 – *Comparison between an isotropic and anisotropic medium. The isotherms showed correspond to year 4.*

In addition, recovery efficiencies reach steady values faster in an anisotropic medium. This phenomenon is depicted in Figure 5.

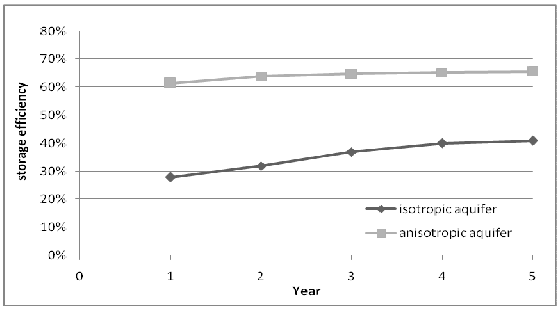

Figure 5 – *Storage efficiency in an isotropic and anisotropic medium.*

The effects of aquifer thickness are shown in Figure 6. A thinner aquifer limits the buoyancy effects.

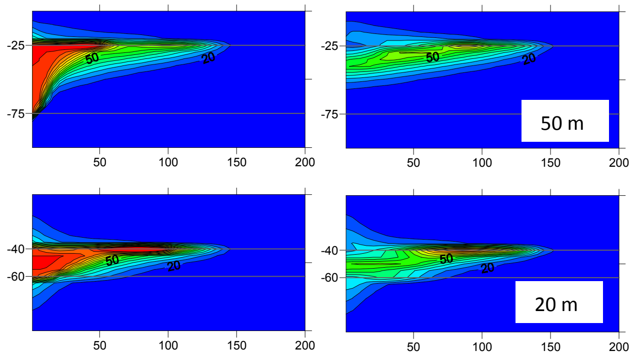

Figure 6 – *Influence of aquifer thickness.*

In Figure 7 the effects of aquifer permeability are shown. The aquifer is assumed isotropic. It can be observed that a higher permeability enhances the bouyant movement of the plume and a lower permeability suppresses free convection and favours a more homogeneous sweep of the thermal plume.

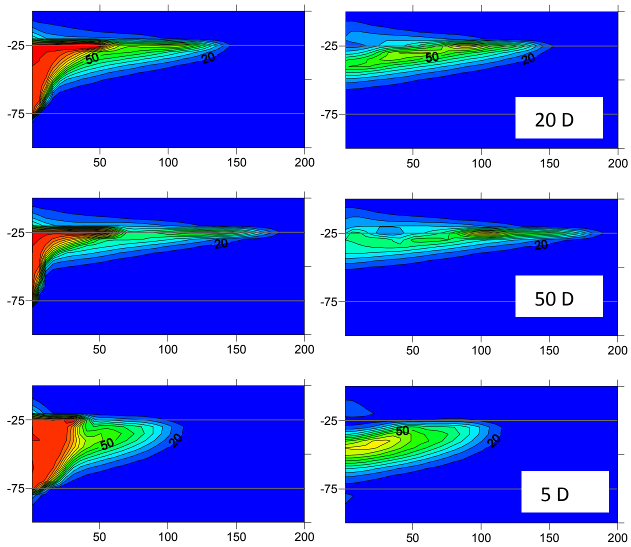

Figure 7 – *Influence of aquifer permeability.*

Recovery efficiency

Free convection is observed in all the scenarios modelled. In a free convection regime, the driving force is the differences in fluid density. A hot fluid is less dense and will tend to rise whilst the surrounding cooler fluid, will move to replace it. However, this cold fluid will then be heated and the process will repeat giving rise to convective currents. In addition, the hot water will tent to stay in the upper part of the aquifer and will create a longer and thinner plume. This enhances heat exchange with the surroundings and keeps the colder temperatures in the lower part of the aquifer. Therefore, during extraction, colder temperatures quickly reach the well decreasing the amount of energy that can be recovered. Table 3 summarises the storage efficiencies obtained for every sensitivity run.

Run #	Recovery efficiency (%)
1	41
2	65
3	26
4	61
5	44
6	57
7	44
8	39
9	56
10	72
11	77
12	75

Table 3- *Recovery efficiencies obtained.*

Rayleigh number and recovery efficiency

The calculated recovery efficiencies are correlated with the Rayleigh number (Ra) and shown in Figure 8. The Ra number indicates the strength of free convection over heat conduction [3]. It is defined as:

$$Ra = \frac{g\rho\alpha H k_v \Delta T}{\mu D}$$

where:
g= gravity acceleration
ρ= density of fluid
μ= dynamic viscosity
α= thermal expansion coefficient
k_v= vertical permeability
D = thermal diffusivity
H = characteristic length scale (taken as the aquifer thickness).
The fluid properties ρ and μ are evaluated at an average system temperature (T_m), defined as:

$$T_m = \frac{T_{min} + T_{max}}{2} = \frac{T_{nat} + T_s}{2}$$

where:
T_{nat}= initial aquifer temperature

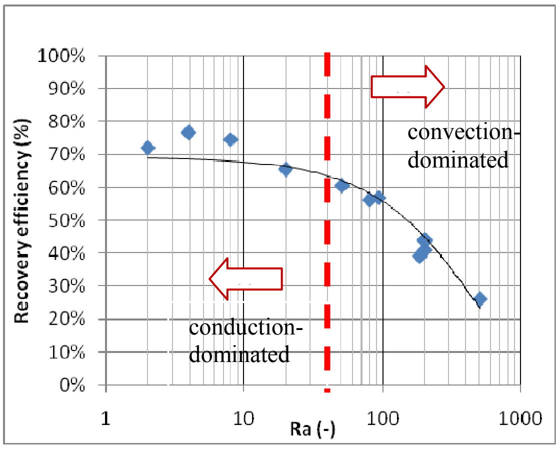

Figure 8 - *Relation between Rayleigh number and storage efficiency.*

Summary and Conclusions

A sensitivity analysis on the recovery efficiency of an HTES system was carried out. Free convection was present in all cases and accounts for most of the heat losses and subsequent impact on the storage efficiency. Other main findings are:

- HTES recovery efficiencies can be correlated with the Ra number which describes the ratio between conduction-dominated heat transfer and convection-dominated heat transfer.
- The fact that storage efficiency can be correlated to the Ra number implies that a HTES project can be pre-designed on the basis of combination of individual parameters, namely aquifer thickness, permeability (vertical) and temperature difference (between initial aquifer temperature and storage temperature).

References

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[2] Kipp, K.L. HST3D: A computer code for simulation of heat and solute transport in three-dimensional ground-water flow systems; USGS, Water-Resources Investigation. 1998Report 86-4095.
[3] D. A. Nield and A. Bejan, Convection in Porous Media. 2nd edition. Springer, New York, 1999.